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14. ABSTRACT
We have performed several experiments involving electromagnetically-induced transparency in acetylene including our studies of slow light in this system. In addition, near the end of the funding period, we have had recent success producing an appreciable density of Rb atoms into the fiber core.

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I) Scientific Personnel: Two PhD candidates (Dimitre Ouzounov, Mark Foster, Chris Hensley) and one post doc (Kevin Moll, Jay Sharping) at different times were supported during this period.

II) List of Manuscripts:

1. M. A. Foster, A. L. Gaeta, Q. Cao, and R. Trebino, and, "Soliton-effect compression of supercontinuum to few-cycle durations in photonic nanowires," *Opt. Express* **13**, 6848 (2005).
2. M. A. Foster, J. M. Dudley, B. Kibler, Q. Cao, D. Lee, R. Trebino, and A. L. Gaeta "Nonlinear pulse propagation and supercontinuum generation in photonic nanowires: experiment and simulation," *Appl. Phys. B* **81**, 363 (2005).
3. V. R. Almeida, C. A. Barrios, Roberto R. Panepucci, M. Lipson, M. A. Foster, D. G. Ouzounov, and A. L. Gaeta, "All-optical switch on silicon," *Opt. Lett.* **29**, 2867 (2004).
4. M. A. Foster and A. L. Gaeta, "Ultra-low threshold supercontinuum generation in sub-wavelength waveguides," *Opt. Express* **12**, 3137 (2004).
5. M. A. Foster, K. D. Moll, and A. L. Gaeta, "Optimal waveguide dimensions for nonlinear interactions," *Opt. Express* **12**, 2880 (2004).
6. D. G. Ouzounov, F. R. Ahmad, A. L. Gaeta, D. Müller, N. Venkataraman, M. Gallagher, C. M. Smith, and K. W. Koch, "Generation of megawatt solitons in hollow-core photonic band-gap fibers," *Science* **301**, 1702 (2003).

III) Conference presentations (Invited):

1) A. L. Gaeta, "Nonlinear optics in photonic crystal fibers," delivered at the Institute of Optics Seminar, University of Erlangen-Nürnberg, in September 2005.
2) A. L. Gaeta, "Slow light in optical fibers," delivered at the Complex Media VI: Light and Complexity Symposium at the SPIE Optics and Photonics Conference in San Diego, CA in July 2005.
3) A. L. Gaeta, "Nonlinear optics in photonic crystal fibers: A new regime of light-matter interactions," (Plenary) delivered at the 2005 Laser Physics Workshop, Kyoto, Japan, in May 2005.
4) A. L. Gaeta, "Nonlinear optics in hollow-core photonic crystal fibers," (Tutorial) delivered at the European Conference on Lasers and Electro-Optics, Munich, Germany, in May 2005.
5) A. L. Gaeta, "Nonlinear optics in photonic crystal fibers: A new regime of light-matter interactions," delivered at the Physics Colloquium, University of Toronto, in March 2005.
6) A. L. Gaeta, "Nonlinear optics in photonic crystal fibers," delivered at the Institute of Optics Colloquium, University of Rochester, in November 2004.
7) A. L. Gaeta, "Nonlinear optics in photonic crystal fibers," delivered at the Ultrafast Lasers Symposium at the SPIE Photonics North Conference in Ottawa, ON in September 2004.
8) A. L. Gaeta, "Nonlinear interactions in photonic band-gap fibers," (Invited) delivered at the Nonlinear Optics Topical Meeting, Waikoloa, HI, August 2004.
9) M. A. Foster, K. D. Moll, "Optimal Waveguide dimensions for nonlinear interactions," delivered at the Nonlinear Optics Topical Meeting, Waikoloa, HI, August 2004.
10) S. T. Cundiff and A. L. Gaeta, "Noise and pulse properties of supercontinuum generation in microstructured fibers," (Tutorial) delivered at the Quantum Electronics and Laser Science Conference in San Francisco, CA, in May 2004.

11) A. L. Gaeta, "Generation of megawatt solitons in hollow-core band-gap fibers," (Invited) delivered at the High-Power Fiber Lasers Symposium at the SPIE Photonics West Conference in San Jose, CA in January (2004).

12) A. L. Gaeta, "Nonlinear interactions in microstructured, band-gap, and hollow fibers," (Invited) delivered at the Summer School on New Frontiers in Optical Technologies, Tampere University of Technology, Tampere, Finland, August 2003.

13) A. L. Gaeta, "Nonlinear interactions in microstructured, band-gap, and hollow fibers," (Invited) delivered at the Gordon Research Conference on Nonlinear Optics and Lasers, New London, NH, July 2003.

14) D. G. Ouzounov, F. R. Ahmad, and A. L. Gaeta, "Solitons generation in a hollow-core photonic band-gap fiber," (Invited) delivered at the 12th International Laser Physics Workshop in Hamburg, Germany in July 2003.

15) D. G. Ouzounov, F. R. Ahmad, A. L. Gaeta, N. Venkataraman, M. Gallagher, C. M. Smith, and K. W. Koch, "Dispersion and nonlinear propagation in air-core photonic band-gap fiber," delivered at the Conference on Lasers and Electro-Optics, Baltimore, MD, May 2003.

16) D. G. Ouzounov, F. R. Ahmad, A. L. Gaeta, N. Venkataraman, M. Gallagher, C. M. Smith, and K. W. Koch, "Generation of high-power, non-frequency shifted solitons in a gas-filled photonic band-gap fiber," (Postdeadline Paper) delivered at the Conference on Lasers and Electro-Optics, Baltimore, MD, May 2003.

II) Inventions: none

IV) Scientific Progress and Accomplishments

During this funding period, we have achieved significant results in four areas:

1) Nonlinear optics in photonic nanowires
2) Coherent nonlinear interactions with atoms and molecules in PBGFs.

We describe our results in each of these areas:

1) Nonlinear Optics in Photonic Nanowires

We have investigated the use of photonic nanowires (i.e., sub-wavelength core fibers) to reduce the threshold power for nonlinear optical processes such as supercontinuum generation. For most nonlinear processes, it is advantageous to maximize the product of light intensity and interaction length, and sub-wavelength waveguides offer a route to maximizing this product. We demonstrated that fabrication of a robust, sub-wavelength core fiber can be achieved by careful tapering of a high air-filling-fraction microstructure fiber yielding a sub-wavelength diameter core. Figure 1 shows an electron micrograph of the initially untapered 2.3-μm fiber and the tapered fiber in which the core size is 650 nm.

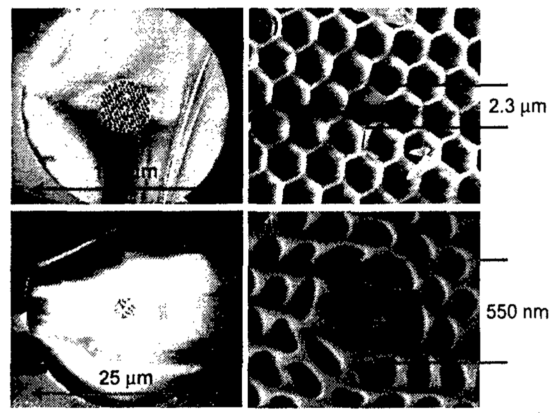


Figure 1: TEM images of untapered (a,b) and tapered (c,d) microstructured photonic-crystal fiber. The 550-nm core in the tapered fibers is near optimal for performing supercontinuum experiments with a 800-nm input pulse.

We generated supercontinuum in this tapered fiber using pulses from modelocked Ti:sapphire oscillator. More than an octave of frequency bandwidth is achieved with pulse energies as low as 125 pJ. In comparison, in the same setup the untapered 2.3-μm-core fiber is unable to generate an octave of bandwidth with energies as large as 1.25 nJ. An additional advantage of the tapered microstructured fiber as compared to tapered conventional fibers is the ability to handle high average powers without damage since the tapered region is well protected from the environment. Our theoretical analysis also indicates that at these small diameters further optimization of all types of waveguides can be achieved by using asymmetric (e.g. oval, rectangular) cores.

Another type of nonlinear interaction in photonic nanowires that we have investigated is high-order soliton pulse compression. Soliton-pulse compression uses the periodic "breathing" behavior of higher-order solitons for which at a certain propagation distance the pulse undergoes significant compression. Such compression only occurs in the presence of anomalous dispersion, assuming that the optical nonlinearity is positive. By utilizing the broad region of anomalous dispersion associated with a sub-micron core waveguide [see Fig. 2(left)] and very short propagation lengths (2 mm) [see Fig. 2(center)], we are able to achieve large compression ratios that we attribute to excitation of a 10^{th}-order soliton. Figure 2(right) shows results in which we demonstrate compression of 70-fs laser pulses at 800 nm down to a few optical cycles with no post-compression.

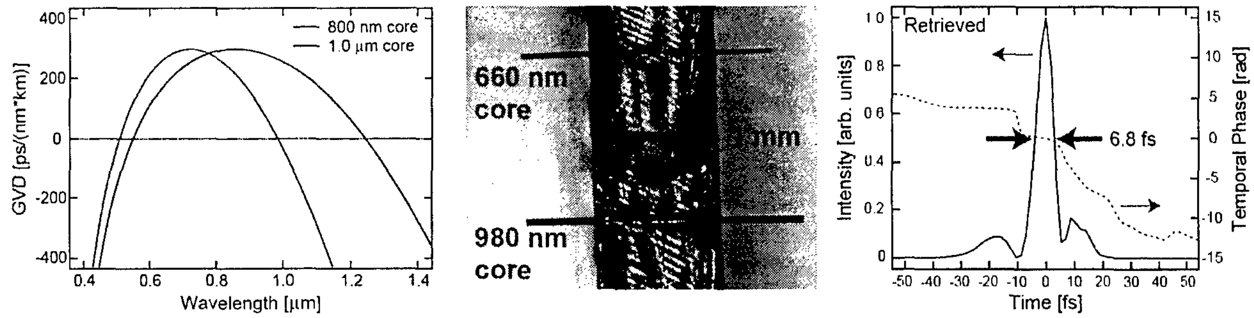


Figure 2: Left: Group-velocity dispersion of 800- and 1000-nm core tapered microstructured photonic-crystal fiber. An octave-spanning region of anomalous dispersion (i.e., GVD > 0) is created which is ideal for performing soliton pulse compression. Center: Optical microscope image of 660-nm and 980-nm core diameter photonic nanowires with 2-mm lengths mounted on a 1-mm metal ridge. Right: Measured amplitude and phase of the compressed pulse for an initial input duration of 70 fs.

2) Interactions with Atoms and Molecules in PBGFs

Characterization of the Linear and Nonlinear Properties of Gas-Filled PBGFs: We systematically characterized low-loss photonic band-gap fibers (PBGF) including ones fabricated by our collaborators from Karl Koch's group at Corning, Inc. In all cases, we find that the fibers exhibit anomalous group-velocity dispersion throughout most of the transmission band (see Fig. 3). In addition, our measurements of the Corning PBGF indicate that the glass matrix contributes a negligible fraction to the optical nonlinearity of the propagating mode and when the fiber core is filled with air the nonlinearity is 1000×smaller than that of current telecommunication fiber. Fibers with such low nonlinearities could potentially support much higher data transmission rates than allowed by the current systems. As a demonstration of the high powers that can be effectively propagated by such a fiber, we demonstrated that it could support soliton pulses with peak powers exceeding 2 MW. Additionally, we could alter the character of the nonlinearity by injecting different gases into the core, and non-Raman shifted solitons with powers exceeding 5 MW were observed (see Fig. 4).

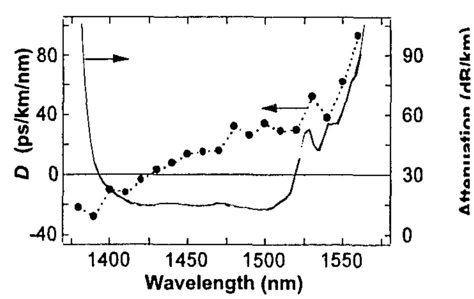
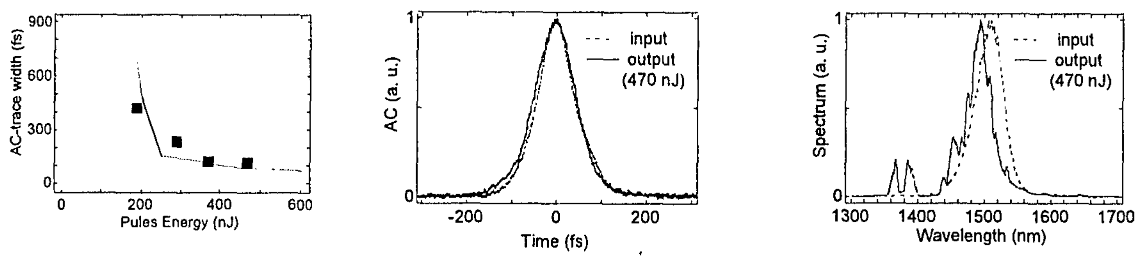


Fig. 3 Measured group-velocity dispersion D and attenuation of a low-loss Corning band-gap fiber.



(a) (b) (c)

Fig. 4. (a) Experimental (squares) and theoretical (solid line) data for the full-width-half-maximum of the intensity autocorrelation trace of the output pulses as a function of the coupled pulse energy. (b) Intensity autocorrelation and (c) spectrum of input and output pulses for a pulse energy of 470 nJ.

Coherent, Resonant Interactions in PBGFs

We have performed several experiments involving electromagnetically-induced transparency in acetylene including our studies of slow light in this system. In addition, near the end of the funding period, we have had recent success producing an appreciable density of Rb atoms into the fiber core.

Acetylene work: We have continued to perform experiments on electromagnetically-induced transparency and slow light with acetylene molecules in PBGFs. Our three-level interaction (see Fig. 5) consists of a control beam tuned between the acetylene levels $0(\Sigma^+_g)$ (J=17) and $\nu_1+\nu_3$ (Σ^+_u)(J=16), and the probe beam is tuned between level $0(\Sigma^+_g)$ (J=15) and the upper level. These are the P(17) and R(15) lines of $^{12}C_2H_2$. The probe power is maintained below 500 μW, and the wavelength of the probe is scanned over the R(15) transition line. Without the control beam we observe the Doppler-broadened absorption of the probe beam with a width of 480 MHz. In the presence of the control beam, a transparency window is opened with greater than 60% transparency. While induced transparencies of this magnitude have been observed routinely in atomic systems such as rubidium, observing this transparency feature in acetylene is remarkable in light of the fact that the dipole moment of the transition is several orders of magnitude less than that for the D_1 and D_2 in alkali vapors.

We have also demonstrated that slow-light effects can be observed in this system. What distinguishes this demonstration of slow light as compared to other examples is that in our system the gas is at room temperature, the light is at telecommunication wavelengths, and the interactions occurs within a fiber. As a result we believe this is an important first step in demonstrating a scheme that could prove useful for telecommunication systems.

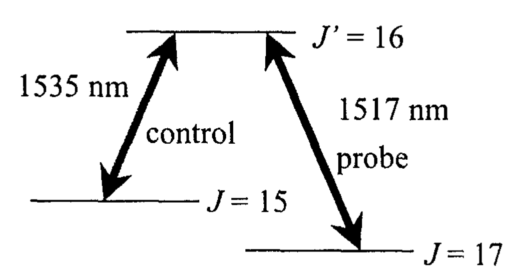


Fig. 5. Three-level system derived from ro-vibrational levels in acetylene.

Rb Atoms in PBGFs: One of the major challenges to create a density of Rb atoms inside the core of a PBGF is its extreme reactivity to different materials. A silica glass wall behaves as a sink for Rb atoms and absorbs the atoms that collide with its surface. As a result, achieving a stable density of Rubidium atoms inside the core of a PBGF is a non-trivial and difficult process, and diffusion alone cannot produce any measurable density within the core. We have recently overcome these obstacles by employing several different mechanisms to produce a significant density within the fiber. Our approach consists of coating the walls of the fiber core with an appropriate film and creating a density of Rb atoms via light-induced atomic desorption (LIAD) to release the atoms from the walls of the fiber. Atoms colliding with these coated walls does not destroy their spin coherence, which can lead to considerable enhancement of relaxation and storage times. Recently, it has also been demonstrated that atoms stuck to these coated walls can be recovered through a non-thermal process where a sudden burst of optical photons breaks the chemical bond with the film and releases the atoms from the surface. In our initial work, we have used micro-fluidic techniques to coat the inside core-wall with a self-assembled mono-layer (SAM) of siloxanes

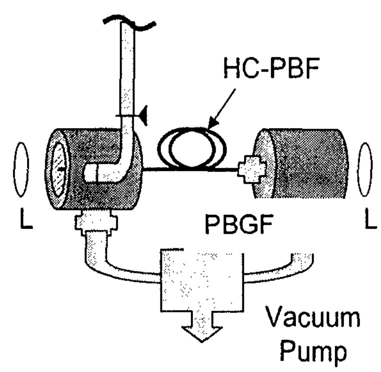


Fig. 6. Dual-cell design for investigating Rb atoms inside PBGF. Each cell is pumped down to high vacuum and atoms pass from one cell to the other through the fiber.

In very recent work, we demonstrate that by coupling a desorpting beam at 795 nm into the fiber we can produce an appreciable density of Rb throughout the length of the fiber (see experimental set up in Fig. 6). We show that the saturation power of the system is ~ 100 nW and that electromagnetically-induced transparency can be performed in this system with extremely low light levels.